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Conceptual Design and Selection of Natural Fibre Reinforced Composite Cyclist Helmet Liner Using an Integrated Approach

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ABSTRACT

This paper describes the conceptual design phase in the product development of a natural fibre composites cyclist helmet liner, beginning with idea generation and ending with selecting the best design concept. The integrated Theory of Inventive Problem Solving (TRIZ), Biomimetic methods, and the Grey Relational Analysis (GRA) method are demonstrated in this paper. This work aims to produce nature-inspired design concepts and determine the best design concept for the composite cyclist helmet liner. Following that, four design concepts were generated using the TRIZ-Biomimetic method, and the variance of concepts was developed using a morphological chart. The GRA method was chosen as the multiple criteria decision-making tool to compare their cost and weight criteria. The design concept C1 was selected as the best design concept for the natural fibre composites of cyclist helmet liner conceptual design when the highest grey relational grade (GRG) value and rank with a value of 1.0000 satisfied the GRA method conditions. This paper demonstrates how the integrated method of TRIZ-Biomimetics-Morphological Chart and GRA helps researchers and engineers develop designs inspired by nature and select the best design concept during the conceptual design stage using a systematic strategy and justified solutions.

Keywords: Biomimetics, concept selection, conceptual design, cyclist helmet liner, GRA, integrated approach, morphological chart, TRIZ

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INTRODUCTION

The recreational, fitness, transportation, and environmentally beneficial benefits

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of cycling have made it a worldwide phenomenon. Common bicycle-friendly cities like Copenhagen, Denmark, and Amsterdam, Netherlands, have cycling participation rates of about 36 % and 34 %, respectively (Pucher et al., 2010; The Worldwatch Institute, 2013), and local governments in various other countries have been encouraging cycling (Leng et al., 2022) due to the health benefits, traffic relief, and environmental benefits. For instance, between 2000 and 2012, the percentage of Americans who rode their bikes to work increased by 61 % (Bliven et al., 2019b; McKenzie, 2014). The Malaysian transport ministry has noticed a rise in cyclists using Malaysian roads for recreational and sporting purposes (https://www.mot.gov.my/en/land/safety/cyclist-safety). Despite its widespread acceptance, cycling is frequently risky. One-third of all visits to the emergency room and three-quarters of all deaths (Høye, 2018, Monique et al., 2023) are due to head injuries (Baker et al., 1993; Bliven et al., 2019a; Rivara et al., 1998).

In particular, traumatic brain injury (TBI) has been labelled the "silent epidemic" because of its potential for delayed effects on human cognition, emotion, and sensitivity (Takhounts et al., 2013). A helmet cuts the risk of fatal brain trauma in a bicycle accident by around half. This rule should be enforced even for short travels (https://www.freemalaysiatoday.com/category/leisure/health/2022/08/23/cycling-an-easy-and-beneficial-activity-for-all-ages/). The shell, liner, and retention straps make up the standard bicycle helmet. The liner is essential because it takes the brunt of the impact, protecting the wearer's head from harm. Liner materials like expanded polystyrene foam (EPS) and expanded polypropylene (EPP) are often utilised (Bliven et al., 2019a). While EPS's low manufacturing cost and high crushing stress-to-weight ratio support its widespread use, it does have some downsides (Blanco et al., 2014).

The benefits of bio-inspired designs have attracted the attention of many researchers working to incorporate them into engineering products. Because of their one-of-a-kind properties, bio-inspired structures can absorb more energy than their artificial counterparts can (Kassar et al., 2016). There has been a recent uptick in academic and engineering interest in eco-friendly product development. Polymer composites can replace traditional petroleum-based plastics to achieve this goal. Polymer composites are used primarily to lessen the vehicle's overall mass, reducing emissions. More stringent regulations and standards for reduced emissions and biodegradability (Ahmad et al., 2015) have led to a steady transition from synthetic fibre composites to natural fibre composites (NFCs). Given their low price, high specific properties, and low density, natural fibre composites have been frequently used to replace synthetic fibres (Al-Ghazali et al., 2022; Pickering et al., 2016; Sapuan & Mansor, 2015). Due to their low cost, lightweight, environmental friendliness, recyclability, outstanding specific strength and stiffness, and image as a natural product (Sapuan & Mansor, 2015), researchers are currently interested in using natural fibre composites (NFC) in various industries. NFC has been used for internal and external parts to replace more expensive materials, including carbon, aramid, and glass fibres.

While bicycle helmets made from synthetic composites are commonplace, attempts to use composites made from natural fibres are far rarer. Bharath et al. (2016) analysed the uses of renewable resource-based natural fibre biocomposite materials, focusing on developing coir-polyester composites for use in helmets. Biocomposite helmet manufacturing methods and mechanical characterisation were presented at an exhibition (Bharath et al., 2018). These studies are among the few that have focused on biocomposites in helmets in recent years. To the authors' knowledge, no natural fibre has been used as a reinforcing component in biocomposites, particularly for creating bicycle helmet liners.

The development process for composite products, encompassing materials, design concepts, manufacturing process choices, and life cycle analysis, must be studied early on in the concurrent engineering process when the product is still in the conceptual design phase (Sapuan et al., 2014). Conceptual design is crucial when making the calls to determine the following stages of product development (Ulrich & Eppinger, 2012; Mansor et al., 2016). The Grey Relational Analysis (GRA) approach was used to select the composite materials for the bicycle helmet. The previous study by the same researchers showed that the pineapple/polyethene composite was the best natural fibre polymer-reinforced composite, with the natural fibre cycling helmet receiving the top ranking, according to the results. This study suggested thermoplastic polyethene as a particularly ideal matrix in composite cyclist helmets during the selection process for the best thermoplastic matrix material using the 6σ technique, with the decision based on the highest performance, the lightest weight, and the most environmentally friendly criteria (Maidin et al., 2023).

The GRA approach was used while evaluating the right natural fibre to fulfil consumer and environmental needs. From the results, the GRA method was utilised and revealed that pineapple was the best-ranked natural fibre among the ten (10) natural fibre alternatives (Maidin et al., 2022). The three phases of conceptual design are ideation (pre-concept), creation (concept design), and evaluation (concept design). Designers and engineers use the ideation approach to develop potential design concepts during this phase. Some ways to create new ideas include brainstorming, blue ocean strategies, biomimicry, and the theory of inventive problem-solving (TRIZ) (Sapuan, 2017). In the early 2000s, researchers started using TRIZ tools with other approaches, such as Quality Function Deployment (QFD) (Yamashina et al., 2002). Teoriya Resheniya Izobretatelskikh Zadach (or TRIZ for short) is a Russian methodology developed by scientist and engineer Genrich Asthuller, who studied over 400 000 patents (Ilevbare et al., 2013). Via its initial problem description and identification, problem-solving methods, and specific solutions (Li et al., 2013), TRIZ aids scientists, engineers, and other industries in addressing difficulties.

At the conceptual design stage, TRIZ can be utilised alone or in conjunction with different approaches to produce ideas for solutions to scientific, technical, and technological problems. In recent years, academics' interest in solving engineering problems through a combination of TRIZ and biomimetics has increased. Scientists believe creating new products can achieve positive environmental outcomes when nature is integrated into engineering technology. Eract Vincent (2009) suggested the TRIZ to understand better how nature and technology interact. In discussing the hybrid approach to product development, Shaharuzaman et al. (2020) detailed the conceptual design phase of a natural fibre composite side-door impact beam (TRIZ and biomimetic). Similarly, using the same method, Yusof et al. (2020) conceptually designed an oil palm polymer composite automobile crash box (ACB). As a means of applying biomimicry functions and TRIZ principles, Lim et al. (2018) developed the TRIZ biomimicry contradiction matrix via text mining and latent Dirichlet allocation (LDA).

This research study explores how the Integrated Method of TRIZ, Biomimetics, and Morphological Chart can be used to design a natural fibre composite bicycle helmet liner conceptually. As a multi-criteria decision-making (MCDM) technique, Grey Relational Analysis (GRA) was used to select the optimal design strategy.

DESIGN BRIEF

Existing research is vital because it provides a roadmap for future studies to adhere to the rules and restrictions outlined for bike helmet liner product design (PDS). PDS also includes geometry limiting rules for cyclist helmet liner profiles. It is essential to know the head circumference of the rider to identify the correct size bike helmet. You can measure the circumference of your head by wrapping a flexible tape measure around the widest part of your head, about an inch above your eyebrows (https://www.rei.com/learn/expert-advice/bicycle-helmet.html). Also, the PDS data can be utilised as a guide when choosing eco-friendly and biodegradable materials to manufacture a low-density product.

In addition, Malaysian authorities only permit helmets with the UN ECE R22. 05 and SIRIM certifications (https://www.motoworld.com.my/index.php?route=blog/post&post_id=48); therefore, the helmet's design must adhere to those standards. ECE R22.05 is an international standard adopted by Malaysia (UN R22.05), where the Economic Commission for Europe is shortened to "ECE". In 1958, the UN formally adopted it to describe rules for cars and bicycles. In this case, 22 refers to Regulation No. 22, updated with the 2005 Series of Standard Amendments. Sixty-two countries have confirmed their acceptance of ECE R22.05. In 1972, the United States Department of Transport released Regulation No. 22, which specified minimum standards for helmets in terms of head coverage, field of vision, user hearing, helmet projections, and material durability. The helmets are tested for inflammability, combustibility, cold, heat, moisture resistance, shock absorption, penetration, rigidity, and chain strap strength. The guideline additionally details the required labelling for helmets. It includes the helmet's dimensions, weight, and donning procedures (https://www.godigit.com/motor-insurance/two-wheeler-insurance/helmets/

helmet-safety-ratings). Finally, the new design for the bicycle helmet's liner must adhere to the specifications in Table 1: Liner thickness of 9 mm, head circumference of 52–64 cm, and maximum cycling helmet weight of 1 kg.

Table 1
Product design specification summary for cyclist helmet (Leng et al., 2022; Kassar et al., 2016; Bhudolia et al., 2021; Novak et al., 2019)

Specification	Description
Head circumference (cm)	52–64
Liner thickness (mm)	9
Weight (g)	<1000

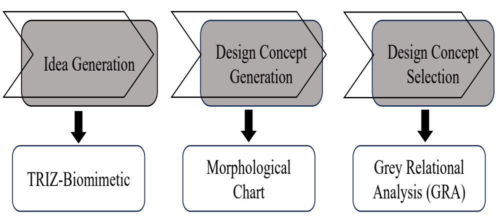


Figure 1. Research methodology based on the TRIZ-Biomimetic and GRA methods

METHODOLOGY

Figure 1 depicts the framework of the natural fibre composite cycling helmet's conceptual design and development process. The TRIZ-Biomimetic approach was first used to generate ideas. Then, a morphological chart might be used to transform the suggestions made by TRIZ-Biomimetic into concrete plans. Afterwards, a 1:1 scale 3D model was created to aid the design process by displaying all the finer details. Finally, utilising the GRA technique, choose the best design idea for the composite cyclist helmet liner.

Specifying Geometry and Generating Ideas with TRIZ-Biomimetic Integration

The TRIZ contradiction matrix for the intended scope of the investigation is displayed in Table 2. 40 TRIZ creative concepts were used to find solutions after an exact match was made between 39 engineering parameters from both sources. The most pertinent principal answers from Table 2 served as the foundation for developing a brand-new cycling helmet liner design. This study aims to develop a novel conceptual design for a cyclist's helmet liner made of natural fibre composites with superior energy absorption properties. So, this design needed a more stringent result, which could be achieved by minimising #2, the Weight of the stationary object. Thus, Inventive Principles #3, Local Quality, and #26, Copying were selected for implementation. The plan's finer points are laid forth in Table 3. Concepts for a new bike helmet liner design were generated using an integrated TRIZ and biomimetic approaches (Table 4).

The TRIZ technique yielded a broad answer, which the designers had to flesh out (Cerniglia et al., 2008). A morphological chart might be used to translate the suggestions made by TRIZ. Moreover, a biomimetic strategy focused on "solving #26. Copying" would use nature's wisdom to address engineering issues (Milwich et al., 2006; Lenau et al., 2009). A cyclist's helmet's traditional outer geometry profile was kept, but the interior was rethought and redesigned to accommodate new ideas and concepts. This iteration of designs uses integrated geometry by considering symmetric body form design alongside the ideas of energy absorption inspired by spider webs (https://www.sutori.com/en/story/biomimicry-in-architecture-spider-web-concept-and-behavior-in-design--9VBrkakv7qv6i7gcmc1KJnYJ), pomelo peels (Ortiz et al., 2018), and honeycombs (https://architizer.com/blog/inspiration/collections/heavenly-honeycomb-buildings/).

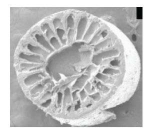
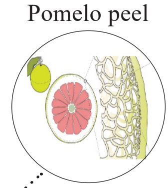
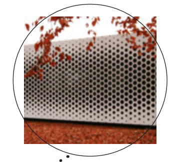
Table 2
TRIZ contradiction matrix for natural fibre reinforced composites cyclist helmet design

39 Engineering parameters		TRIZ principle solutions to 40 inventive principles
Improving parameters	**Worsening parameters**	
#2. Weight of stationary object	#8. Volume of stationary object	#2 Taking out #26 Copying #40 Composite materials #6 Universality
	#27. Reliability	#10 Preliminary action #40 Composite materials #8 Anti-weight #3 Local quality
	#14 Strength	#15 Dynamics #28. Mechanics Substitution #40 Composite materials #8 Anti-weight

Table 3
Details of conceptual design strategy

TRIZ solution principle	TRIZ recommended solution	Strategy for design
#40. Composite materials	Change from uniform to composite (multiple) materials	Use composition where pineapple fibre with reinforced thermoplastic polyethene for maximum energy absorption by raising composite toughness
#26. Copying	Use simpler and inexpensive copies (virtual reality, natural); replace an object or process with optical copies	Biomimetic methods provide intellectual concepts inspired by nature (how plants or animals absorb energy during collisions to survive and save their lives)
#3. Local quality	Make each part of an object function in conditions most suitable for its operation; Make each part achieve different and useful functions	Creating optimum cross section using a hybrid method to strengthen structure (combination of two or more biomimetics elements)

Table 4
Integrated TRIZ, morphological chart, and biomimetics methods for cyclist helmet concept generation

TRIZ solution principle and design strategy	**Design feature**	**Solutions**			
		1	**2**	**3**	**4**
#26. Copying	Liner design	Spider web 	Hedgehog spine 	Pomelo peel 	Honeycomb 
Biomimetic methods provide intellectual concepts inspired by nature (how plants or animals absorb energy during collisions to save and survive their lives)	Absorb energy by	Sudden impact	Raised to stand on end	Outstanding damping	Strong structure
#3. Local quality Creating the most optimum body shape using a hybrid approach to strengthen structure (combination of two or more biomimetics elements)	Body shape	Symmetrical		Asymmetry	
	Body type	Foam	Shell	Combined geometry	Multilayer

Designing a Concept for a Cyclist's Helmet by Combining TRIZ, Biomimetics, and Morphological Charts

Figure 2 shows four new ideas for bike helmets using a mix of TRIZ, biomimetics, and morphological charts. The 3D model was made on a 1:1 scale, making it easier to see how the design elements fit together. C1 said that the first design idea copied the spiderweb structure for the liner. The spider orb-web frame silk structure is more potent per unit weight than high-tensile steel, with a very high toughness of 2.5108 J/m^3 or 1.5105 J/kg (Gosline et al., 1986). It means spider web structures can take in much energy when hitting something (Du et al., 2011; Ko et al., 2004). For the second concept idea, C2, the model was made in a honeycomb shape. They used a honeycomb structure, which can be light, intense, last a long time, and save money (Boria & Forasassi, 2008; Gavrila & Rosu, 2011). The third idea, C3, for the liner of a cyclist's helmet, was based on pomelo peel. In recent years, researchers have become interested in the structure of pomelo peel because it is so good at damping and releasing energy (Ortiz et al., 2018). Model C4 combines spiderweb and honeycomb structures to make a very dense model. All concept designs had the same standard external geometry profile to keep the shape and function of bike helmets the same (Cristóbal et al., 2018).

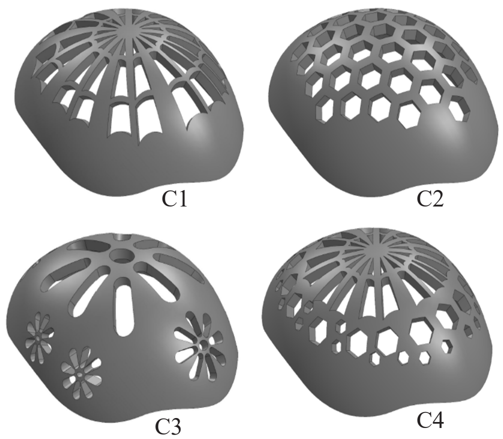


Figure 2. 3D CAD model of new liner cyclist helmet concept designs

The GRA Method to Choose the Best Concept Design for a Cyclist's Helmet

The grey relational analysis is an impact assessment model measuring how similar the comparability and reference sequences are by comparing their relationship grades. For the study's calculations, Microsoft Excel 2016 was used. There are four main steps to the GRA method. The first step is making a grey relational sequence, which includes making a comparability sequence referring to the attributes of each option. A perfect target or reference sequence similar to the developed grey relational series is well-defined after converting all performance criteria into a single comparability sequence. After that, the grey relational coefficient is calculated for each attribute. The final step is to determine the grey relational grade (GRG) from the coefficients and weights given to the performance attributes. The GRG found is used to rank the options (Geum et al., 2011; Jayakrishna & Vinodh, 2017; Maidin et al., 2022).

Two main attributes and the sub-attributes that go with them were taken from the PDS main document. The data came from recent and well-known literature, and cyclists' opinions were gathered using an electronic survey questionnaire sent to helmet-wearing cyclists. It was done to determine the most important thing in designing helmet liners. Both aspects of the conceptual design were chosen to help us determine what was most important to them. Cost and weight are the most important considerations when selecting a concept design for a cyclist's helmet, as shown in Figure 3. The better a part can absorb energy, the less weight it has. Also, the design must be cost-effective. It can be done by leaving out optional

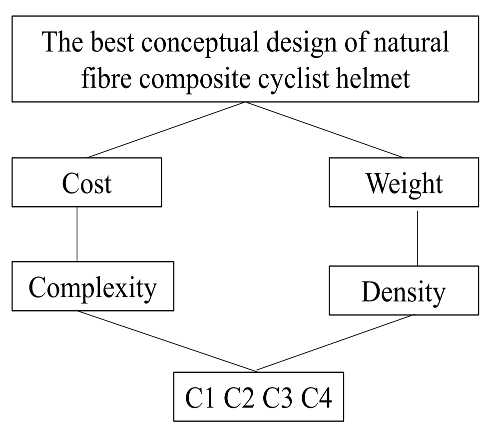


Figure 3. GRA framework for pineapple fibre polymer composites cyclist helmet concept design selection

features when making the part. The goal of the project was set at the top level. The relative importance of each of the compared criteria was based on the numerical values seen in the attributes of the overall cyclist helmet concept designs (Table 5). The part's volume and mass were calculated using the Solidworks 2021 software. These values were calculated numerically based on the properties of the pineapple material found in other research studies. The cost of this project is related to the manufacturing complex. The value is marked with a 0 and 1, representing low to medium scale, respectively.

Table 5
Overall concept design attributes of pineapple polymer composite cyclist helmet liner (Leng et al., 2022; Maidin et al., 2023; Maidin et al., 2022; Kassar et al., 2016; Geum et al., 2011; Jayakrishna & Vinodh, 2017; Bhudolia et al., 2021; Novak et al., 2019)

Parameter	C1	C2	C3	C4	GRA Generating
Mass (g)	446.41	459.47	465.21	453.17	SIB
Volume (mm^3)	372009.7	382895.5	387677.5	377643.5	SIB
Manuf. complex	0	1	1	1	SIB

Poisson’s ratio: 0.394, Tensile strength: 898.5 MPa, 1 = medium, 0 = low

The design for concept 1 used less material and was thus considered less expensive than the others that used more material, such as designs for concepts 2, 3, and 4. However, concept 2 was the easiest to draw and design during the design stage, followed by concepts 3 and 4, whereas concept 1 was the most difficult to create due to the complicated elements.

RESULTS AND DISCUSSION

The best design concept was chosen using Grey Relational Analysis (GRA), a multi-criteria decision-making (MCDM) method. The concept selection process calculation was prepared at the outset of the research. However, it has not been presented here for the sake of brevity. The entire evaluation results using the GRA method are presented in Table 6. Overall, the GRA results of the cyclist helmet concept design selection demonstrated that the C1 design scored the highest grey relational grade (GRG) with a value of 1.0000, followed by the C4 design with a value of 0.4989 at the second rank. The third and fourth ranks are from C2 and C3, with grades of 0.3901 and 0.3333, respectively. Along with the general conclusions, each concept criterion’s scores were recorded and transformed into a graph (Figure 4).

The Distinguishing Coefficient (δ) is a crucial component of GRA, a top multi-criteria decision-making (MCDM) model of grey system theory, which was created by Chinese researchers in the 1980s (Deng, 1989). However, generally, researchers assume $\delta = 0.5$, whereas the present study adapted this practice (Maidin et al., 2022; 2023). According

Table 6
Findings of grey relational grade and rank for natural fibre composites of cyclist helmet liner conceptual design

CONCEPT	GRG	RANK
C1	1.0000	1
C4	0.4989	2
C2	0.3901	3
C3	0.3333	4

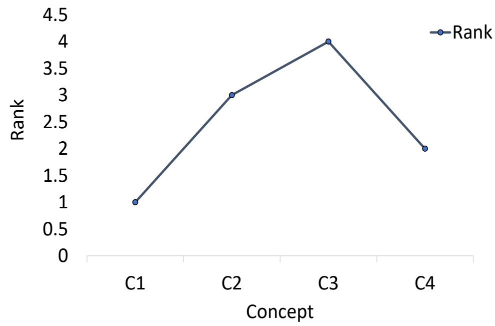


Figure 4. GRA final synthesis results with respect to all criteria

to other researchers, the values δ variance have little impact on the components' GRA rankings. The study, however, showed that differences in δ may impact the rank order (Mahmoudi et al., 2020). Primarily, the distinguishing coefficient in this investigation was set at 0.5, and the result is shown in Figure 5. Figure 6 depicts the results for grey relational coefficients when various distinguishing coefficients were utilised. In addition, as part of error analysis, this work assessed the effect on GRA results when the differentiating coefficients were adjusted to 0.1, 0.3, 0.7, and 0.9, correspondingly. The consistency of the results is shown in Table 7.

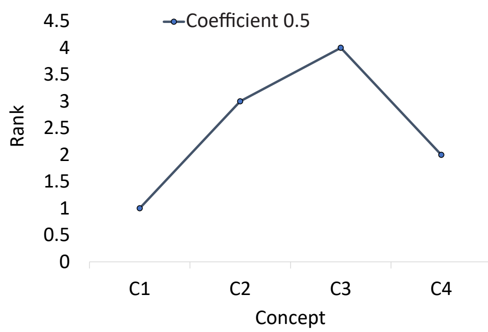


Figure 5. The distinguishing coefficient of 0.5

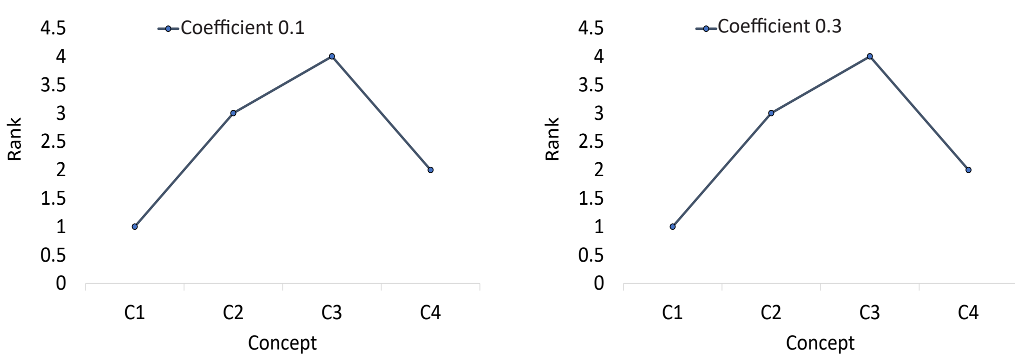
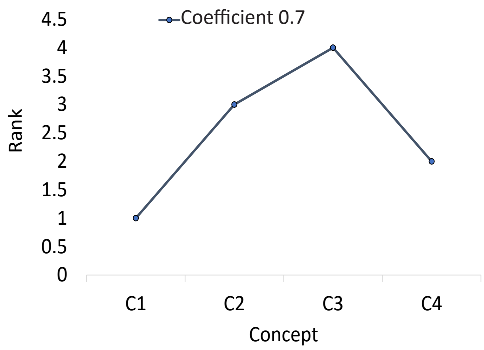


Figure 6. Impact of distinguishing coefficient on the results of GRA to find the best natural fibre composites of cyclist helmet liner conceptual design



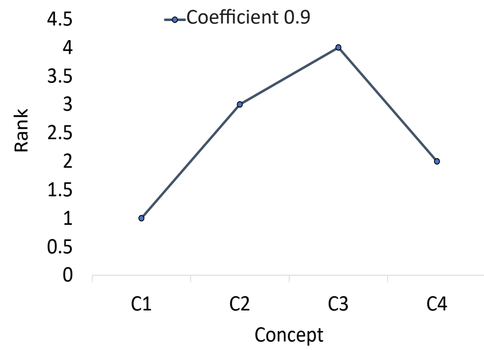


Figure 6. Continue

Table 7
Error analysis summary based on five circumstances

Rank	Original Results	0.1	0.3	0.5	0.7	0.9
#1	C1	1	1	1	1	1
#2	C4	2	2	2	2	2
#3	C2	3	3	3	3	3
#4	C3	4	4	4	4	4

CONCLUSION

After the GRA design selection, concept design C1 was selected as the best design concept for the natural fibre composites of cyclist helmet liner conceptual design when the highest grey relational grade (GRG) value and rank were compared. The generated results were acceptable due to the consistency value throughout the evaluation. Besides that, the stability of validation of the analysis was obtained by changing the multi-distinguishing coefficient value for error analysis, still ranked the C1 design first among the three designs. As a result, there was justification for approving the suggested design. Furthermore, the hybrid TRIZ-Biomimetics-Morphological Chart method revealed the ability to be used in conceptual design idea generation, enhancement, and development. Moreover, the GRA method has been shown as a systematic method in the process of conceptual design selection to achieve the goal or design solution, mainly when undertaking the conceptual design of natural fibre composites of cyclist helmet liners.

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